Corso di Dispositivi Elettronici - A. A. 2004/2005

Basics of RF Devices

Mainstream electronics
(processors, ASICs, memories)

Semiconductors

- Si

Transistor Types

- MOSFETs
- For a few applications BJTs

- Governed by Moore's Law
- Increasing number of devices per chip
- Scaling (decreasing device size)
- CD < 1 µm around 1987 (commercially)
- Si MOSFET dominates

RF electronics

Semiconductors

- III-V compounds based on GaAs and InP
- Si and SiGe
- Wide bandgap materials (SiC and III-nitrides)

Transistor Types

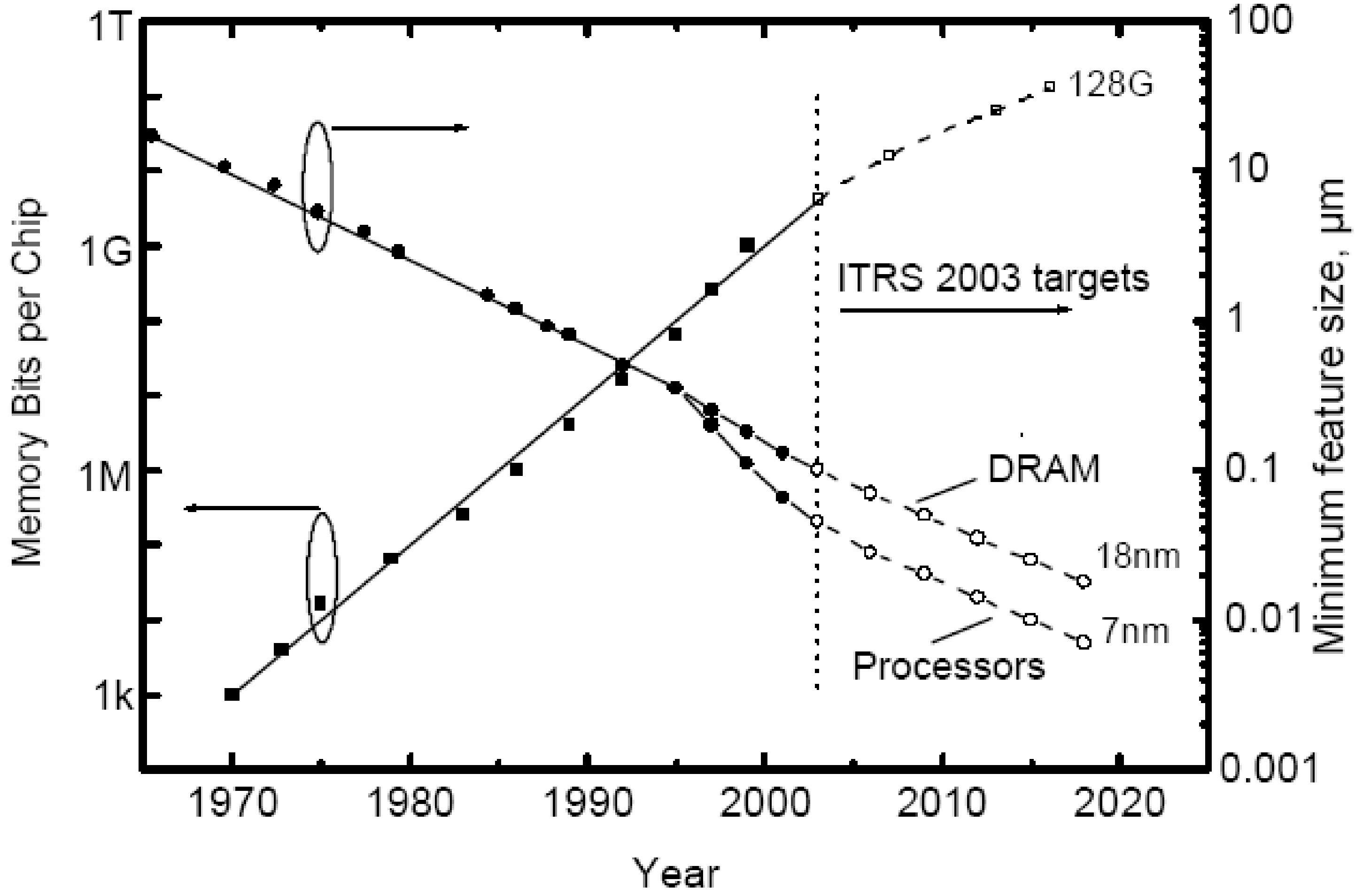
- MESFET - Metal Semiconductor FET
- HEMT - High Electron Mobility Transistor
- MOSFET - Metal Oxide Semiconductor FET
- HBT - Heterojunction Bipolar Transistor
- BJT - Bipolar Junction Transistor

RF electronics

- Moore's Law is not an issue
- Integration is less important
- Traditionally a submicron technology
- Commercial devices

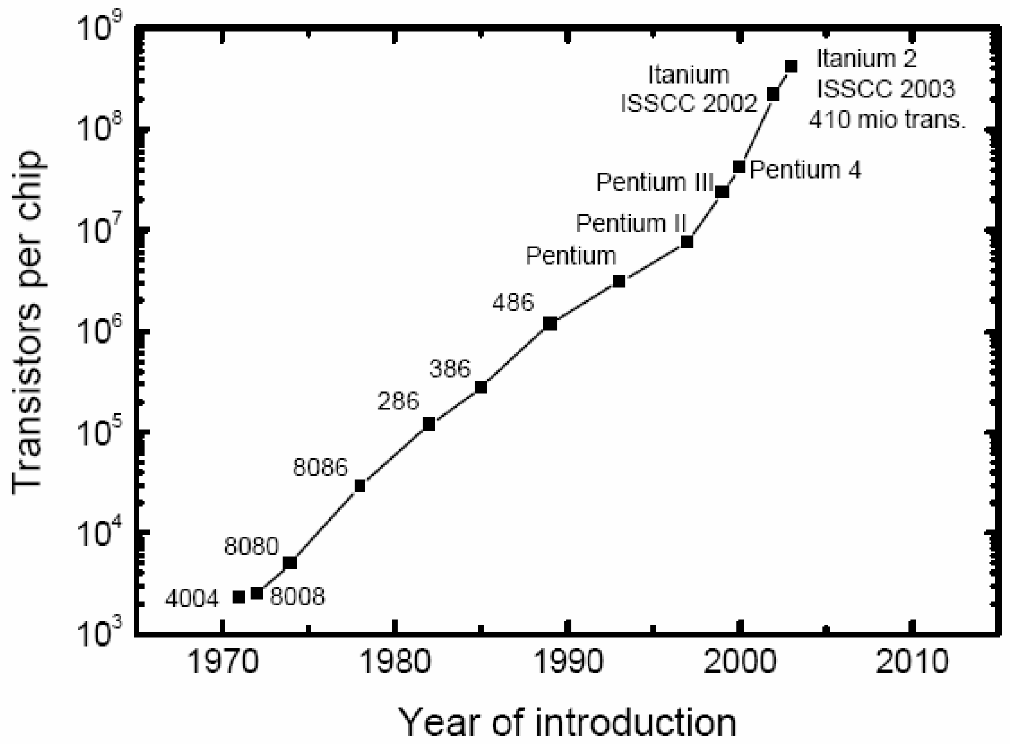
1980 0.5 - 2 µm
1982 0.25 - 1 µm
2004 0.05 - 0.5 µm

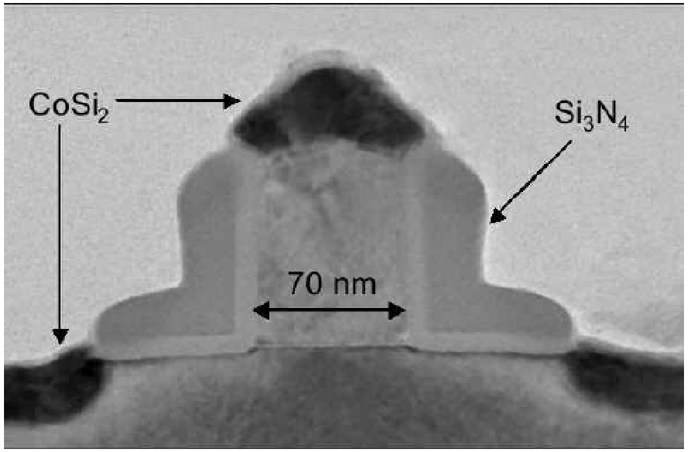
Mainstream electronics



Mainstream electronics

Evolution of Intel Processors

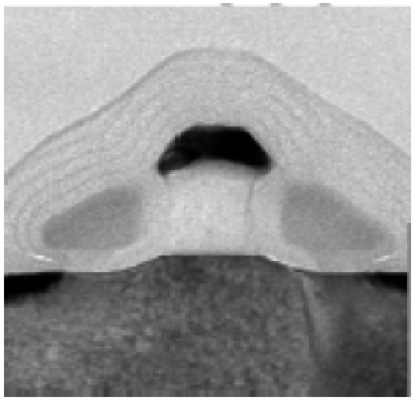




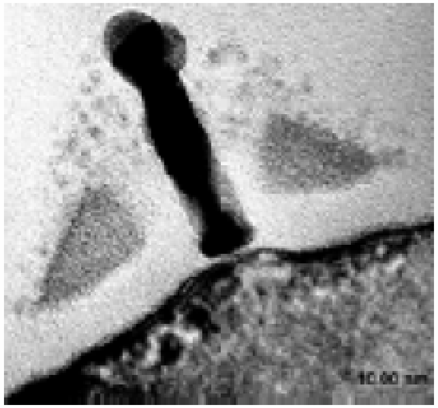
Intel MOSFET with 70 nm gate

More than 40 Mio. transistors of this type are integrated on a single Pentium 4 chip.

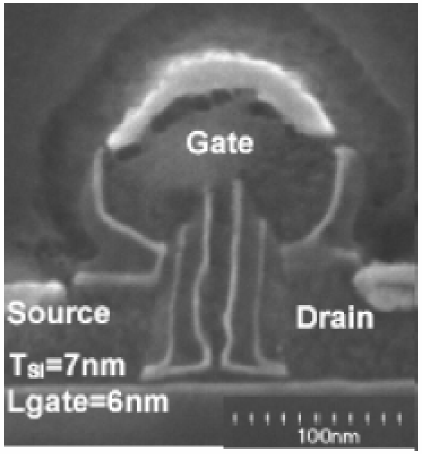
Mainstream electronics is on the way to nanoelectronics



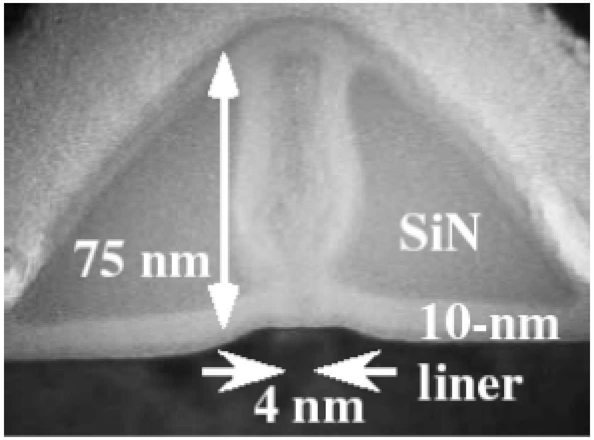
IEDM 2000
Intel 30nm



DRC 2003
Intel 10nm

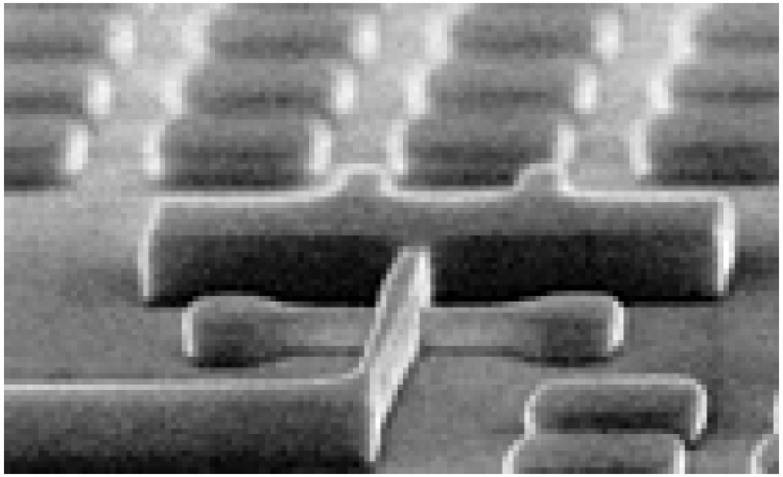


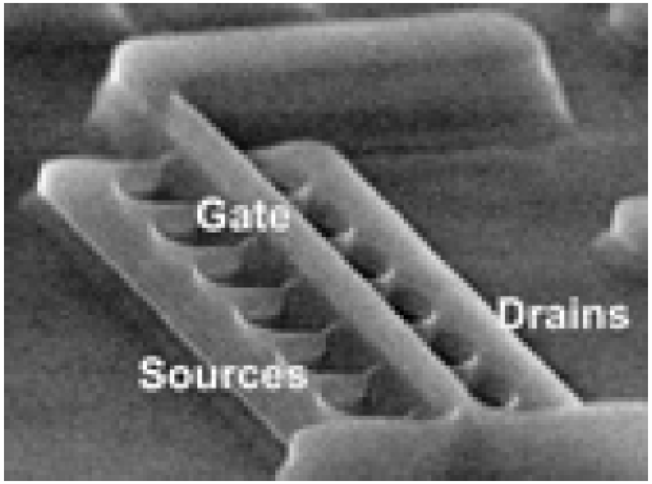
IEDM 2002
IBM 6nm



IEDM 2003
NEC 5nm

Intel's new Tri-Gate MOSFET





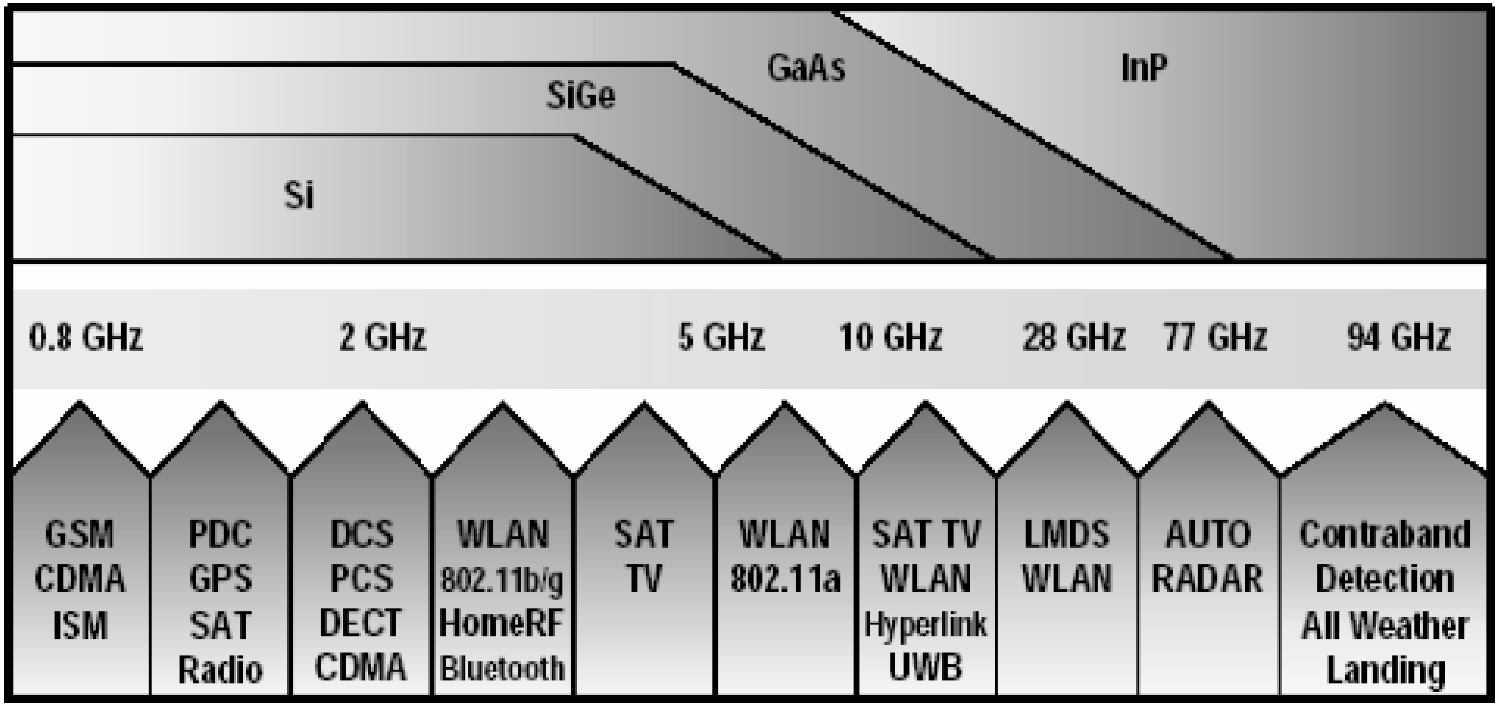
- Smaller and smaller devices
- New MOSFET concepts
- But: Si still dominates
  MOSFET still dominates

Market Trends

- **by 1980** Only military applications, RF is synonymous with mysterious. Philosophy: Performance at any price.
- **1980s-90s** Increasing number of consumer applications
- **Late 1990s** Clear shift from military to consumer applications, explosion of the market for mobile communications. Now: reasonable performance at lowest price.
- **2001** Considerable turbulences, layoffs. There are no markets with unlimited growth!
- **2003/2004** Recovery. In the medium and long term, RF electronics will still grow dynamically. New applications will be introduced.

Market Trends

Applications



Taken from: ITRS 2003 Edition.

Chapter *Radio Frequency and Analog/Mixed-Signal Technologies for Wireless Communications*

Acronyms

- GSM Global System for Mobile Communications
- CDMA Code-Division Multiple Access
- ISM Industrial, Scientific and Medical (frequency bands)
- PDC Personal digital cellular
- GPS Global Positioning System (Satellite)
- DCS Digital Communication System
- PCS Personal Communications system
- DECT Digital European Cordless Telephone/Telecommunications
- WLAN Wireless Local Areal Network
- UWB Ultra-Wideband

Transistor Concepts I

Two basic transistor concepts

- FETs (Field-Effect Transistor)

  The output current (mainly a drift current) is controlled by a perpendicular field.

  The conductivity of the channel is varied by changing the potential of a control electrode (gate).

  - MESFETs (Metal-Semiconductor FET)
  - HEMTs (High Elexctron Mobility Transistor)
  - MOSFETs (Metal-Oxide-Semiconductor FET)

- Bipolar transistors

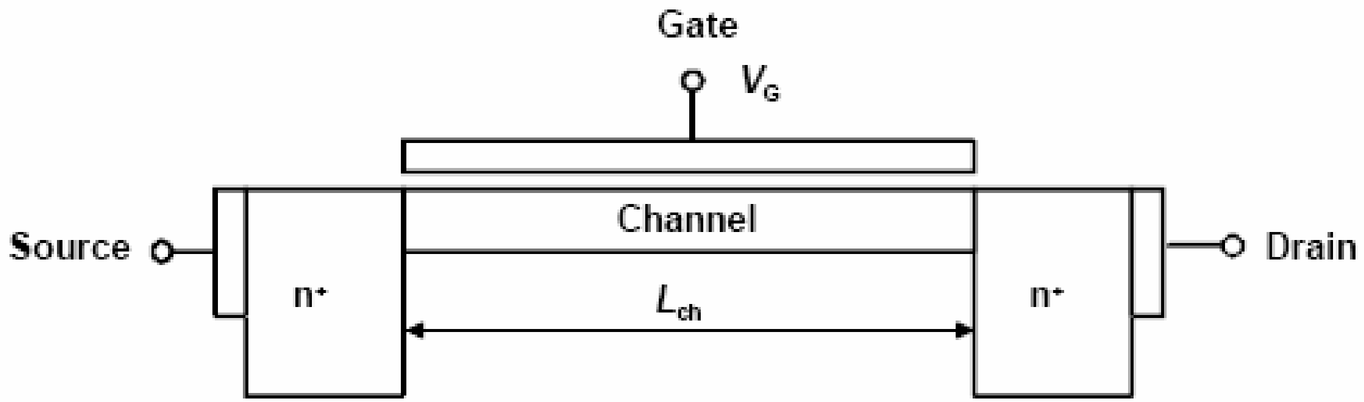
  The output current (mainly a diffusion current) is controlled by the voltage across a pn junction.

  The carrier injection is varied by changing the voltage across the junction.

  - BJT (Bipolar Junction Transistor)
  - HBT (Heterojunction Bipolar Transistor).

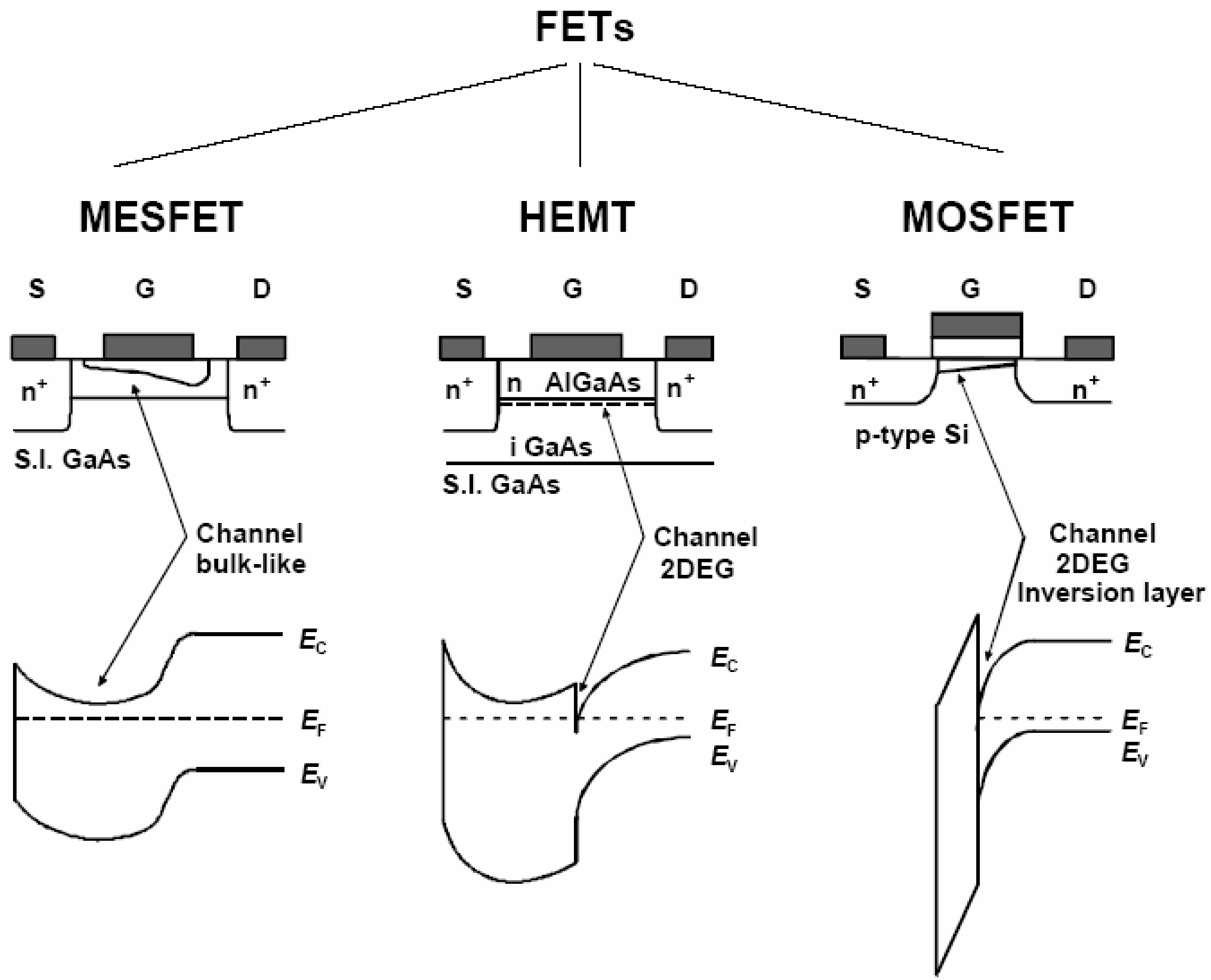
Transistor Concepts I - FETs

A FET in general



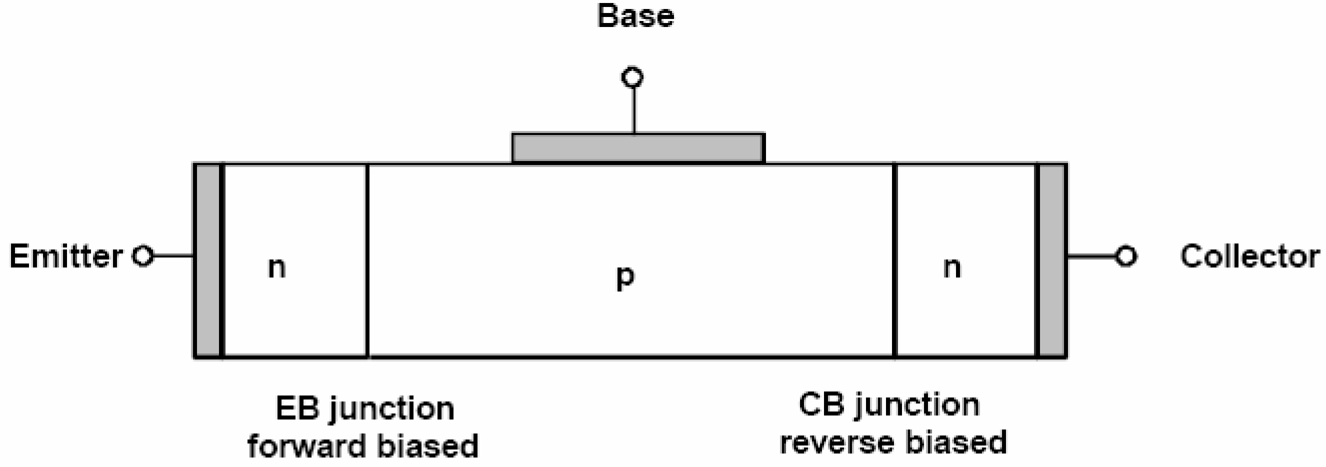
RF FETs use n-channels. A more positive gate voltage increases the number of carriers (electrons) in the channel

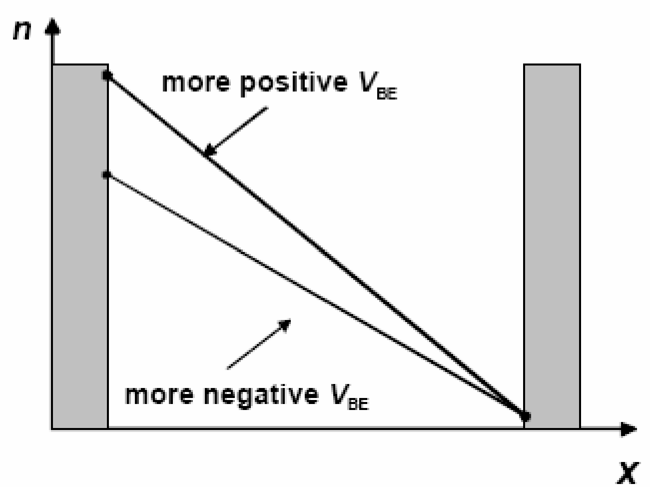
Transistor Concepts I - FETs



Transistor Concepts I - Bipolars

A bipolar transistor in general





Bipolar transistors

- BJT
  - same material for emitter and base
  - EB junction is a homojunction
- HBT
  - different materials for emitter and base
  - EB junction is a heterojunction
  - emitter: wider bandgap
  - base: more narrow bandgap

How to Make a Transistor Fast ?

An RF transistor has to react as fast as possible on a variation of the input signal

FET – gate voltage V_G

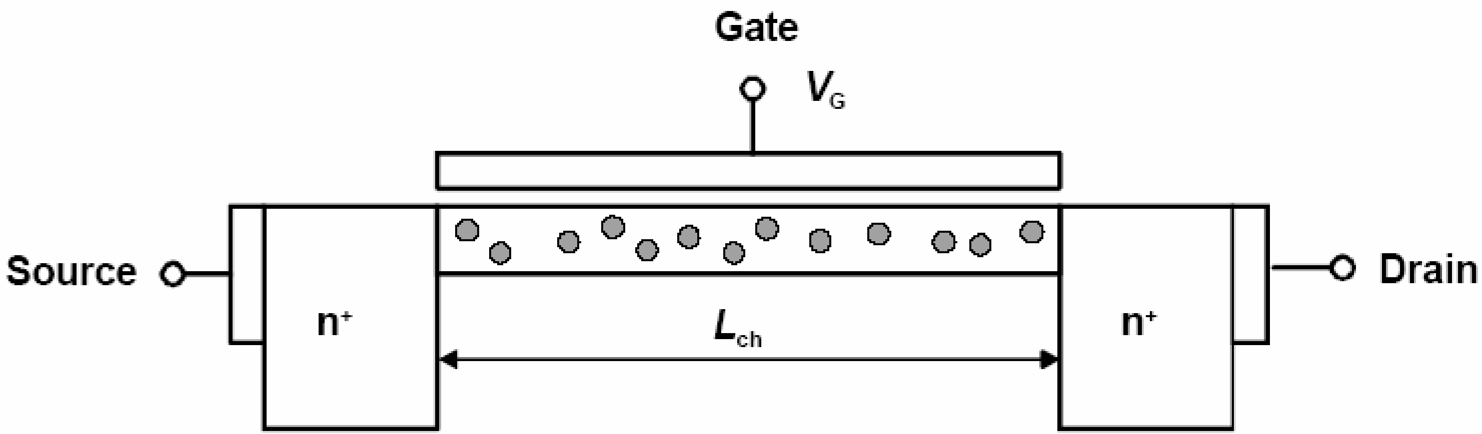
Bipolar Transistor – base voltage V_B
(base current I_B)

- Material Issues
Most important: Fast carriers

- **The charge distribution in the active region of the transistor has to be changed.**

- **To achieve this we have to consider**
  - Transistor Design
  Small active region of the transistor.
  Critical dimension – FET: gate length L
  – Bipolar: base thickness (width) w_B

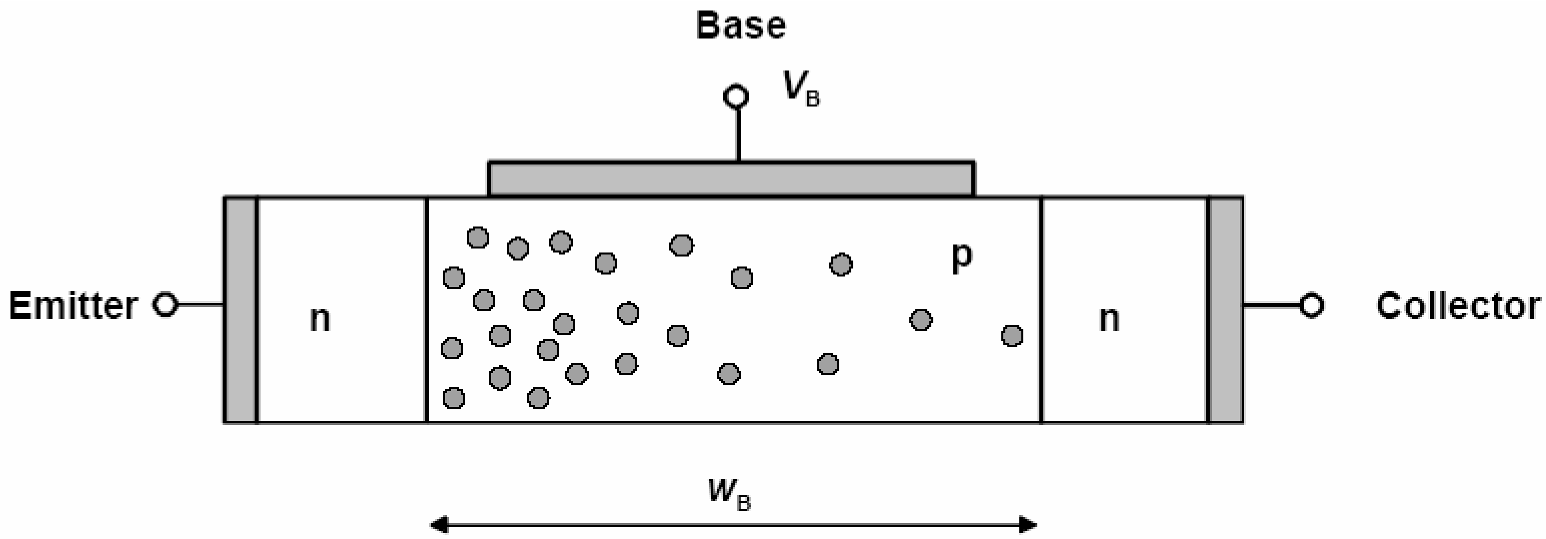
How to Make a FET Fast ?



Design:
- short channel (small L_{ch})
- fast carriers (n-channel)

Material:
- fast carriers
  (high mobility, high velocity)

How to Make a Bipolar Transistor Fast ?



Design:
- narrow base (small w_B)
- fast carriers (npn)

Material:
- fast carriers
  - high mobility
  - high velocity
- high diffusivity

RF Transistor FOM (Figures of Merit)

The two most important features of a transistor are:
- its ability to amplify (important for analog and RF electronics)
- its ability to act as a switch (important for digital electronics)

Important Figures of Merit (FOMs) of RF transistors

RF power transistors

- Gain (power gain, current gain)
- Frequency limits f_T and f_{max}
- Output power
- ...

RF low-noise transistors

- Gain
- f_T and f_{max}
- Minimum noise figure
- ...

FOMs – Power Gains

Power Gain
General definition:

$$G = \frac{P_{out}}{P_{in}}$$

Microwave electronics - several power gain definitions.

Frequently used are:
- **Maximum stable gain *MSG***
- **Unilateral power gain *U***
- **Maximum available gain *MAG***

Example: Definition of *U*
Power gain of a two-port having no output-to-input feedback, with input and output conjugately impedance matched to signal source and load, respectively.

$$U = \frac{\left| y_{21} - y_{12} \right|^2}{4\left[Re(y_{11})\ Re(y_{22}) - Re(y_{12})\ Re(y_{21}) \right]}$$

Power gains are frequently given in dB:

$$Power\ \ Gain\left[dB\right] = 10\log\left(Power\ \ Gain\right)$$

FOMs – Current Gain and Noise Figure

Current Gain
General definition:

$$|h_{21}| = \left|\frac{i_2}{i_1}\right| = \left|\frac{y_{21}}{y_{11}}\right|$$

Current gain in dB

$$|h_{21}|\,[dB] = 20\log_{10}|h_{21}|$$

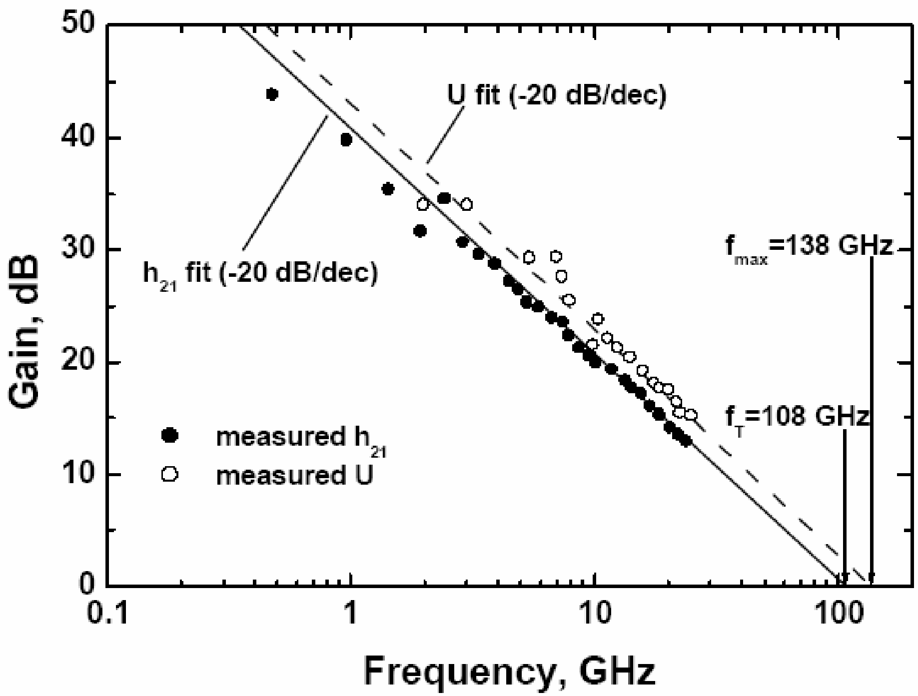
Noise Figure

NF **describes the noise generated in the transistor. Should be as small as possible and is always above 0 dB in real transistors. For optimum matching and bias conditions, *NF* reaches a minimum - the minimum noise figure NF_{min}.**

$$NF\,[dB] = 10\log\frac{P_{Si}/P_{Ni}}{P_{So}/P_{No}}$$

2:

FOMs – The Characteristic Frequencies f_T and f_{max}



Measured h_{21} and *U* of a GaAs MESFET
After K. Onodera et al., IEEE Trans. ED 38, p. 429.

h_{21} and *U* roll off at higher frequencies at a slope of –20 dB/dec.

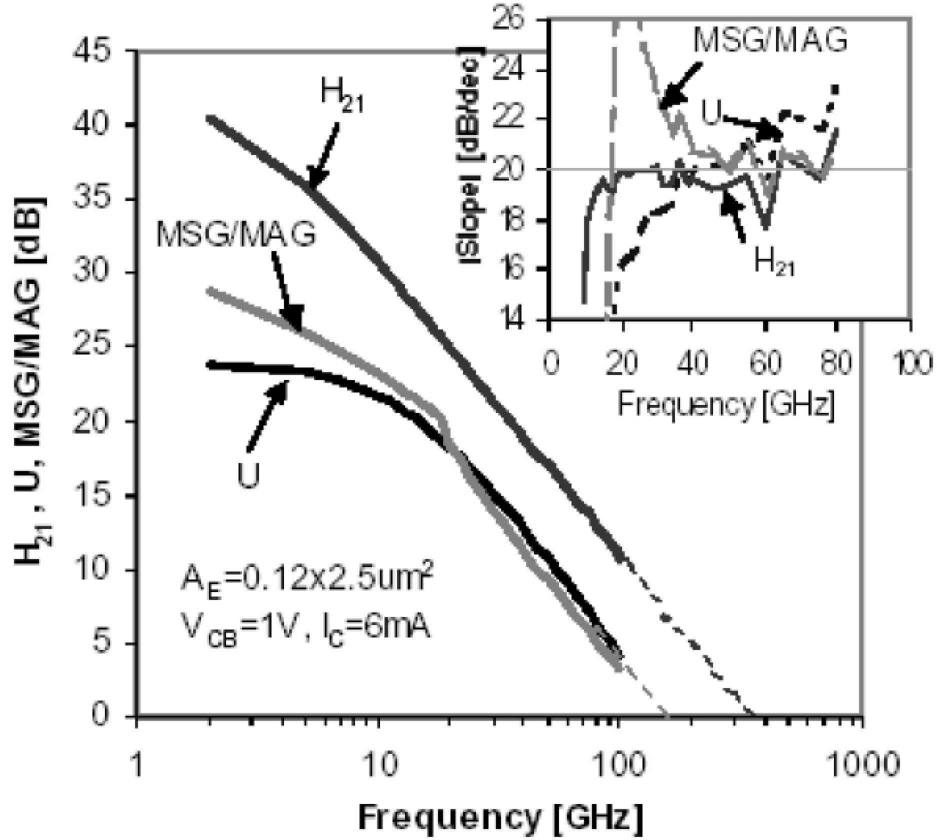
Cutoff Frequency f_T
Frequency, at which the magnitude of the short circuit current gain h_{21} rolls off to 1 (0 dB).

Maximum Frequency of Oscillation f_{max}
Frequency, at which the unilateral power gain *U* rolls off to 1 (0 dB).

Attention: Frequently f_{max} is NOT extrapolated from measured *U*, but from measured *MAG* or *MSG* !

Check before working with published f_{max} values !

FOMs – The Characteristic Frequencies f_T and f_{max}



Measured h_{21}, MSG, MAG, and U of a SiGe HBT
Ref.: J.-S. Rieh et al., IEDM 2002.

FOMs – The Importance of f_T and f_{max}

A frequently asked question:

Is the extrapolation of h_{21} and U with –20dB/dec actually useful?

The answer is: definitely YES !

1. **P. Greiling (1984)**
   "For those of us associated with this technology, this measurement problem always seems to exist. We are in a catch 22 situation in which we are developing circuits for instruments that are needed to measure the circuits we are developing."

2. **If we know the extrapolated f_{max} we find the power gain U at any frequency according to:**

$$U(f) = -20 \log f + 20 \log f_{max}$$

3. **Using f_T and f_{max} we can compare the RF potential of different transistors reported somewhere in the literature.**

FOMs – f_T and f_{max} vs f_{op}

Rule of thumb

$$\boxed{f_T \sim n \times f_{op},\ f_T \sim f_{max}}$$

- Low-noise transistors: $n \sim 10$ (conservative) , i.e., f_T should be around $10 \times$ the operating frequency f_{op} of the RF system in which the transistor is to be used.
- Power transistors: $n \sim 5$.

What does this mean?

If $n = 10$ and $f_T = f_{max}$, we have 20 dB unilateral power gain U at f_{op}. Note that U is the upper limit for the power gain a transistor can achieve. The actual gain in a realistic circuit environment, e.g. G_a for minimum noise, will be several dB lower.

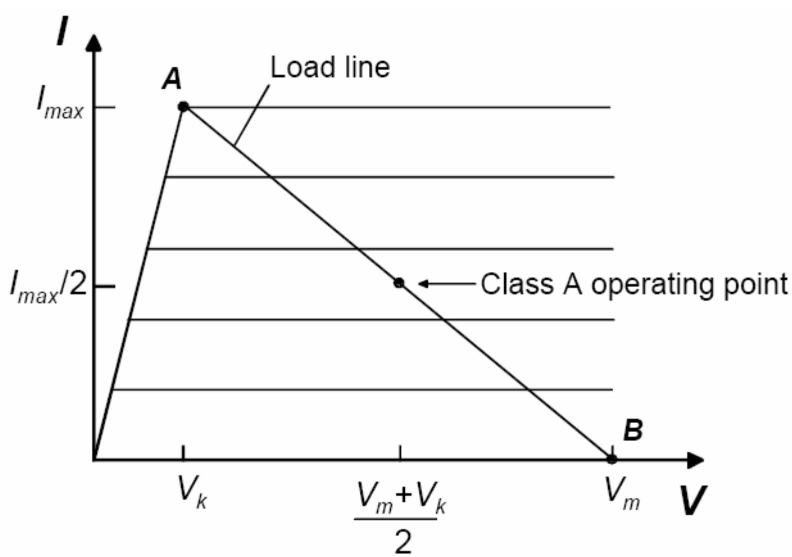
Examples:

GaAs MESFET:	f_{max} = 70 GHz	U @ 12 GHz = 15.3 dB, G_a @ 12 GHz = 11 dB
AlGaAs/GaAs HEMT:	f_{max} = 50 GHz	U @ 12 GHz = 12.4 dB, G_a @ 12 GHz = 9 dB
AlGaAs/GaAs HEMT:	f_{max} = 120 GHz	U @ 18 GHz = 16.5 dB, G_a @ 18 GHz = 11.6 dB

FOMs – Output Power

Amount of RF power in Watt (W) that can be delivered from a transistor to the load.

General definition: $$P_{out} = \frac{1}{T}\int_0^T R_L\, i_L^2$$



Class A amplifier

$$P_{out} = \frac{I_{\max}\left(V_m - V_k\right)}{8}$$

FOMs – Output Power

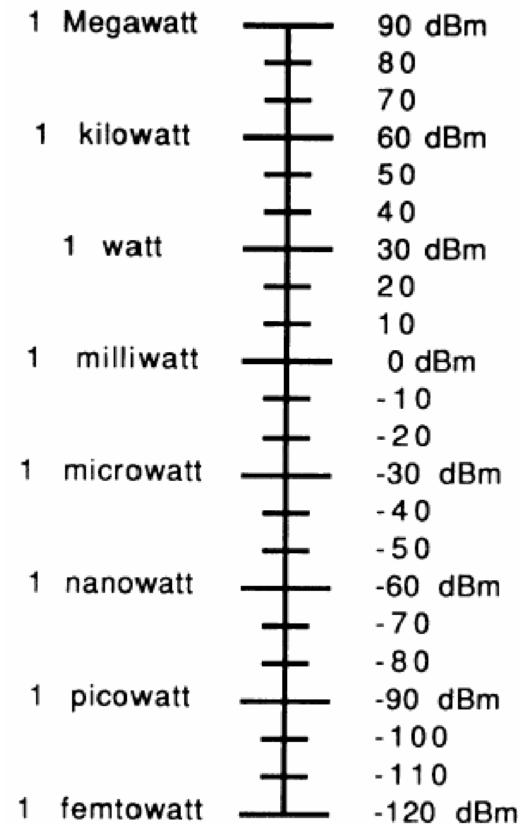
The output power is frequently given in dBm:

$$P_{out}\left[dBm\right] = 10\log P_{out}\left[mW\right]$$

$$P_{out}\left[mW\right] = 10^{P_{out}\left[dBm\right]/10}$$

Examples:

1 mW = 0 dBm	-10 dBm = 0.1 mW
10 mW = 10 dBm	30 dBm = 1000 mW = 1 W
20 mW = 13 dBm	40 dBm = 10 W
100 mW = 20 dBm	50 dBm = 100 W



Ref.: A. W. Scott, Understanding Microwaves, J. Wiley 1993

A FOM related to the output power is the output power density P_{Dout}:

- **P_{Dout} in W/mm gate width (FETs)**
- **P_{Dout} im mW/µm² emitter area (bipolar transistors)**

Material Issues

Most Important for high speed (high f_T and f_{max}) and for low noise:

Fast carriers, i.e. - high low-field mobility (μ_0)

- high peak and/or saturation velocity (v_{peak} , v_{sat})

Important for high output power:

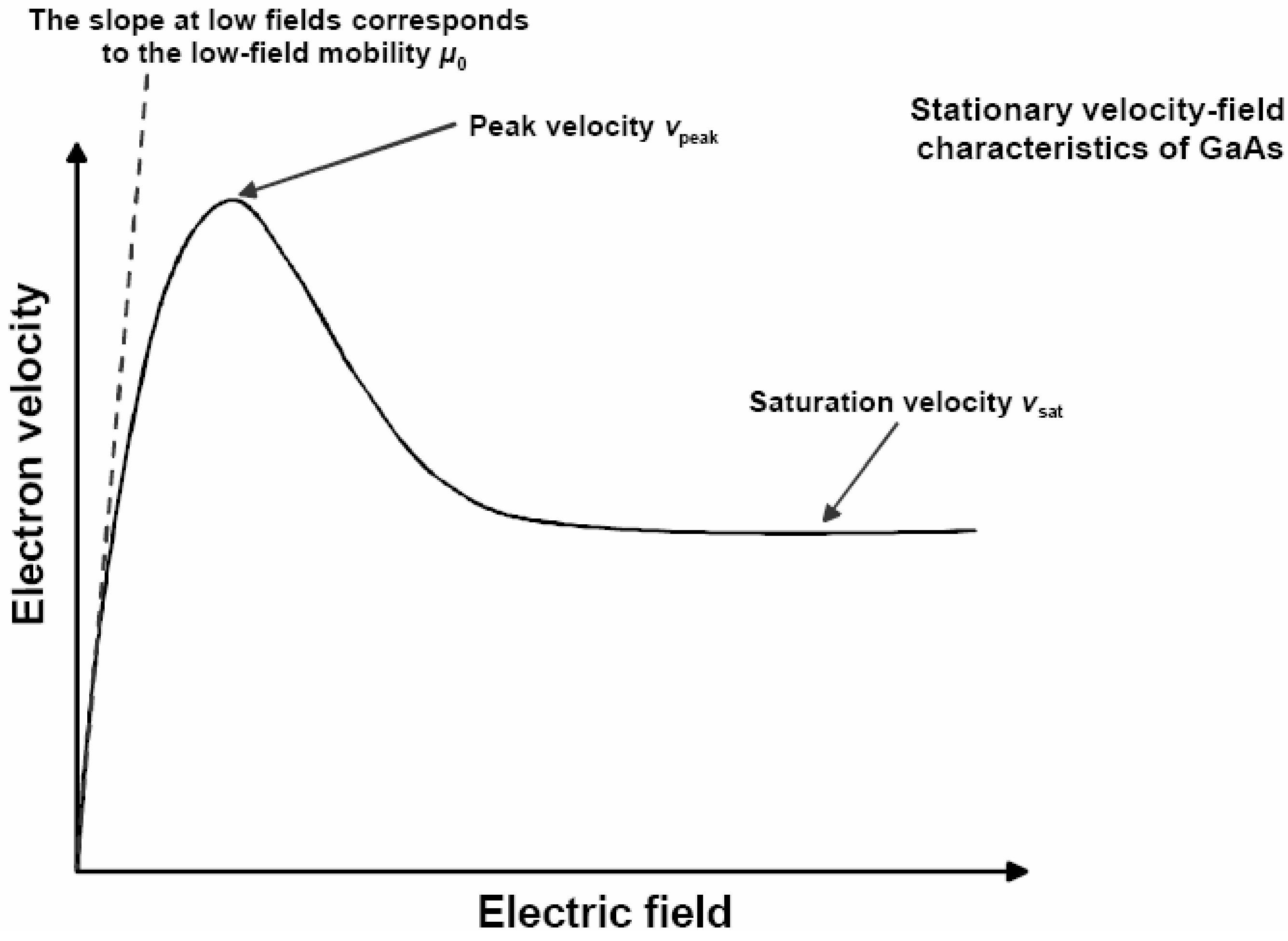
- high breakdown voltage, i.e. wide bandgap

- high thermal conductivity

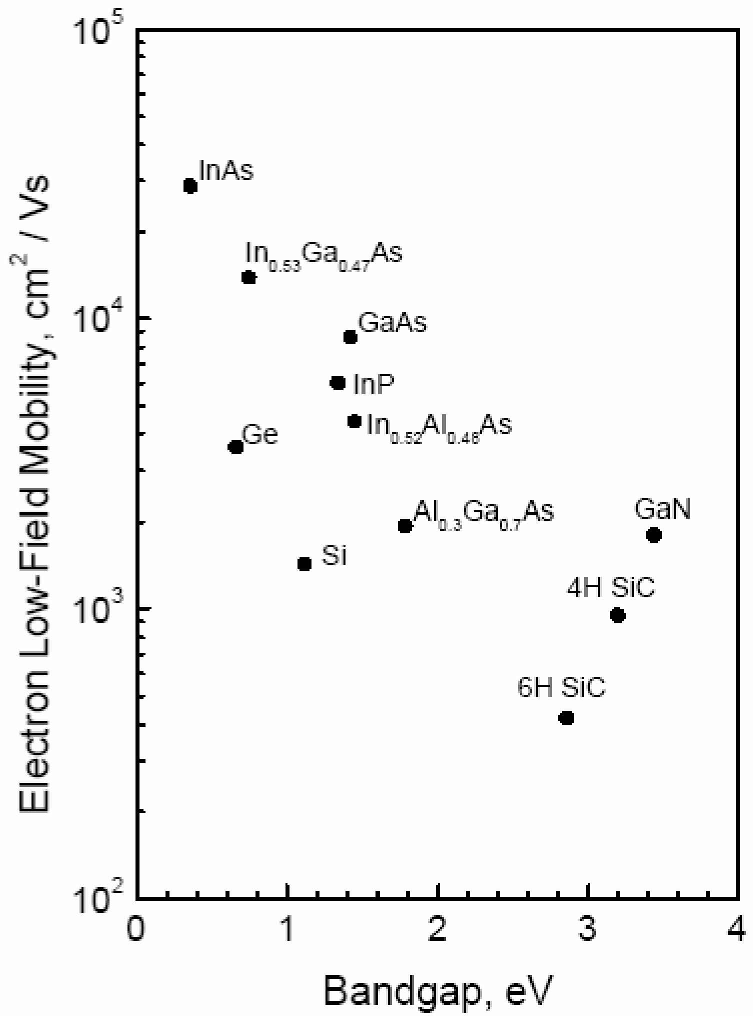
	Si	GaAs	$In_{0.47}Ga_{0.53}As$	4H SiC	GaN
E_G, eV	1.12	1.42	0.74	3.2	3.44
E_{BR}, 10^5 V/cm	5.7	6.4	4	33	44
μ_0, cm²/Vs	710	4700	7000	610	830
v_{peak}, 10^7cm/s	1	2	2.5...3	2	2.5
v_{sat}, 10^7cm/s	1	0.8	0.7	2	1.5...2
κ, W/cm-K	1.3	0.5	0.05	2.9	1.2

Data for n-type material with $N_D = 10^{17}$ cm^{-3}

Low-Field Mobility and Drift Velocity



Low-Field Mobility



Carrier velocity at low electric field:

$$v = \mu_0 \times E$$

In any semiconductor the electron mobility is larger than the hole mobility.

Thus, for RF applications transistors where electrons carry the main current are preferred:

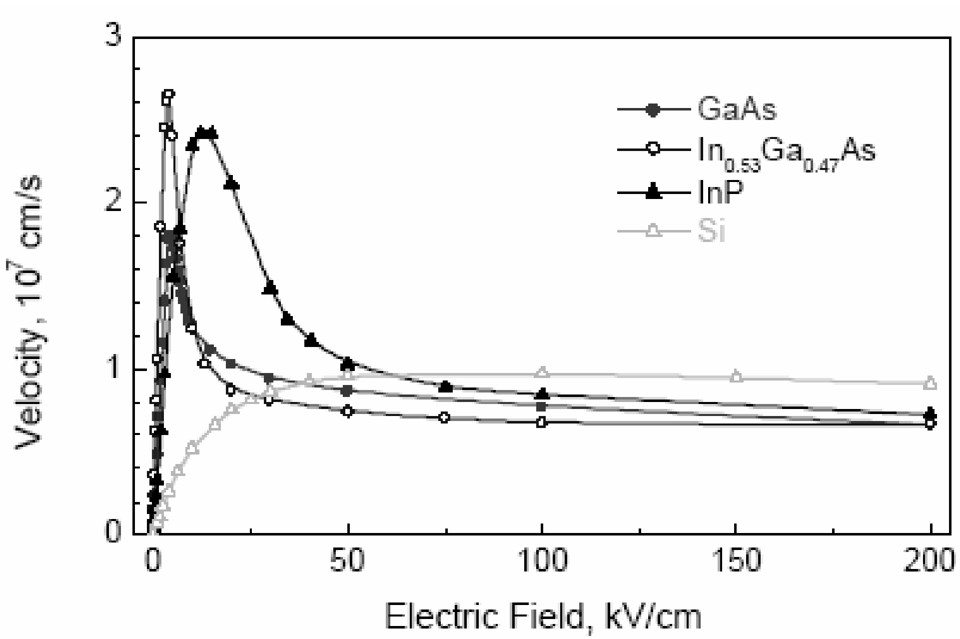
n-channel FETs
npn bipolars

low-field mobility of electrons (undoped material, T = 300K)

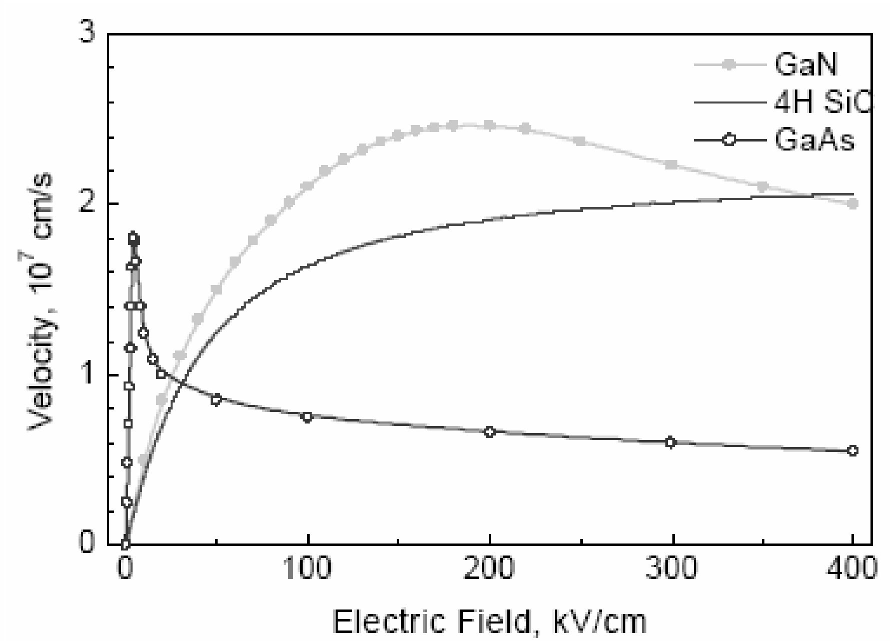
Drift Velocttity

Stationary velocity-field characteristics (*v*-*E*)

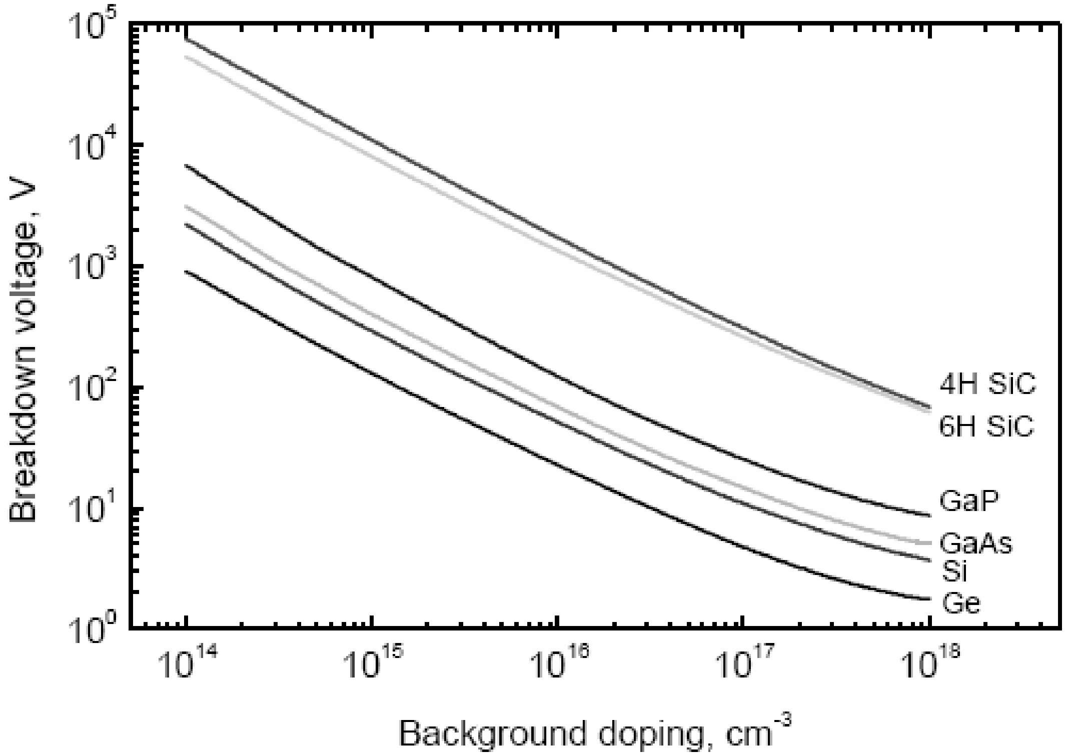
Si and III-V semiconductors



Wide bandgap semiconductors



Breakdown Voltage



Breakdown voltage of abrupt one-sided pn junctions as a function of doping (at the low-doped side)

The breakdown voltage is closely related to the breakdown field.

Bandgap increases

4H SiC E_G = 3.20 eV
GaAs E_G = 1.42 eV
Ge E_G = 0.66 eV

A large bandgap results in a large breakdown voltage.
For power transistors a high breakdown voltage is important.
LARGE POTENTIAL FOR WIDE BANDGAP MATERIALS!

Heterostructures

Heterostructures

- are semiconductor structures consisting of at least two different semiconductors
- are uncommon in mainstream electronics
- are frequently used in RF transistors
  - FETs: HEMTs
  - Bipolars: HBTs
- The RF transistors showing
  - the highest f_T and f_{max}
  - the highest output power densities
  - the lowest noise

  are heterostructure transistors.

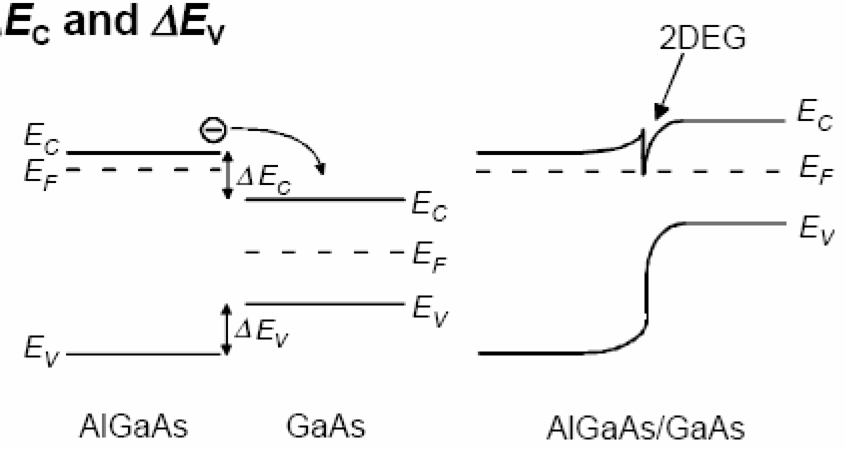
Therefore it is useful to discuss some aspects of heterostructures in the following.

Heterostructures

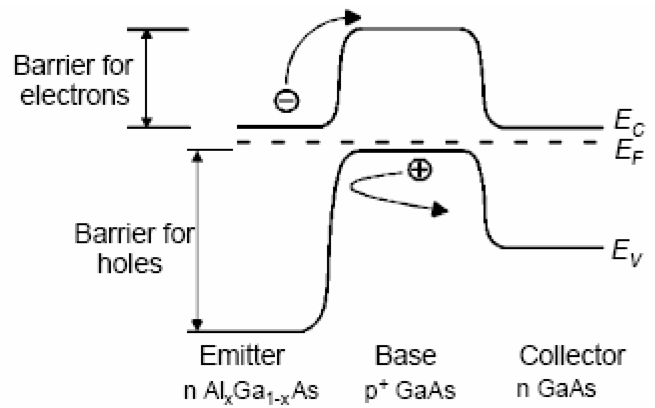
The physics exploited in RF heterostructure transistors

Most important: band offsets ΔE_C and ΔE_V

HEMTs
(here: AlGaAs/GaAs HEMT)

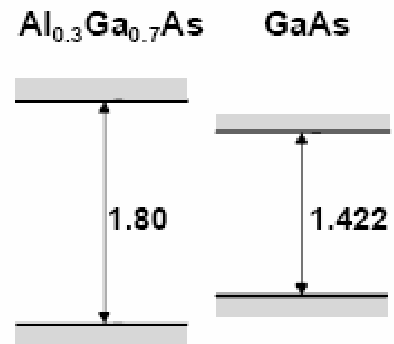


HBTs
(here: AlGaAs/GaAs HBT)

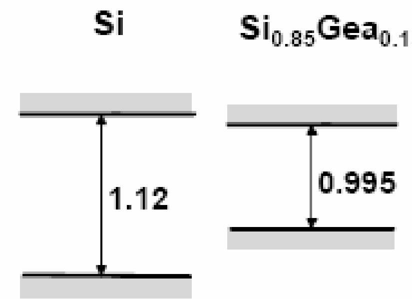


Heterostructures

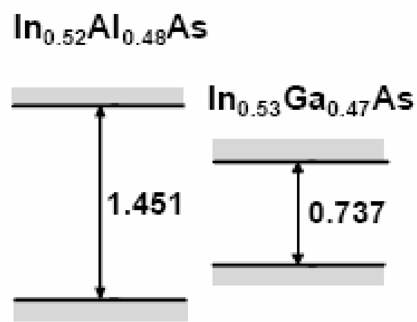
Semiconductor pairs frequently used in heterostructures



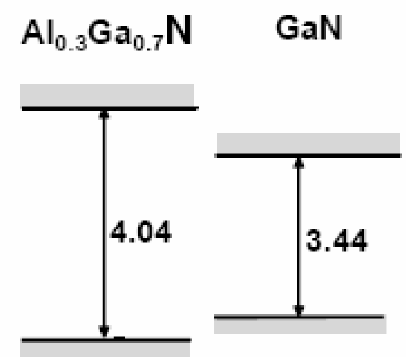
$\Delta E_C = 0.219$
$\Delta E_V = 0.159$



$\Delta E_C = 0.02$
$\Delta E_V = 0.105$

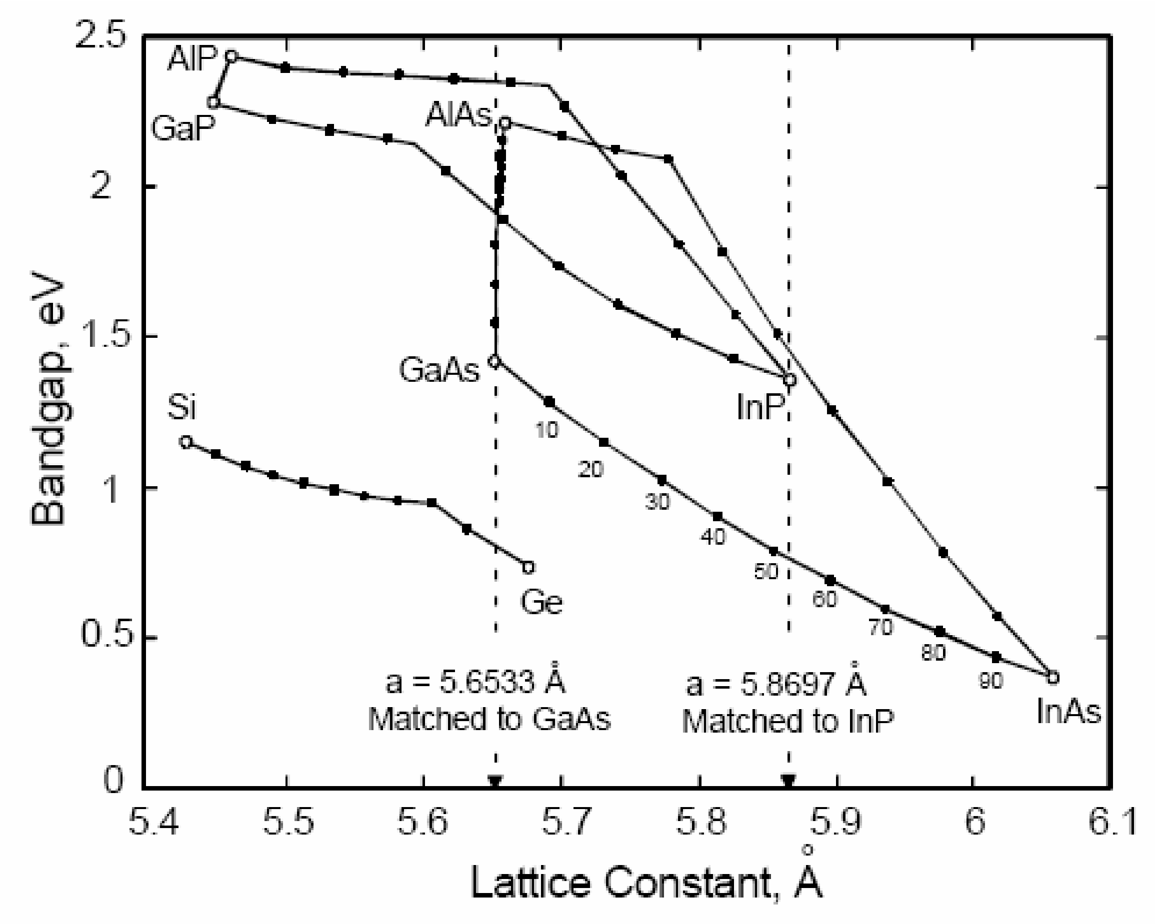


$\Delta E_C = 0.52$
$\Delta E_V = 0.194$



$\Delta E_C = 0.42$
$\Delta E_V = 0.18$

Bandgap vs Lattice Constant



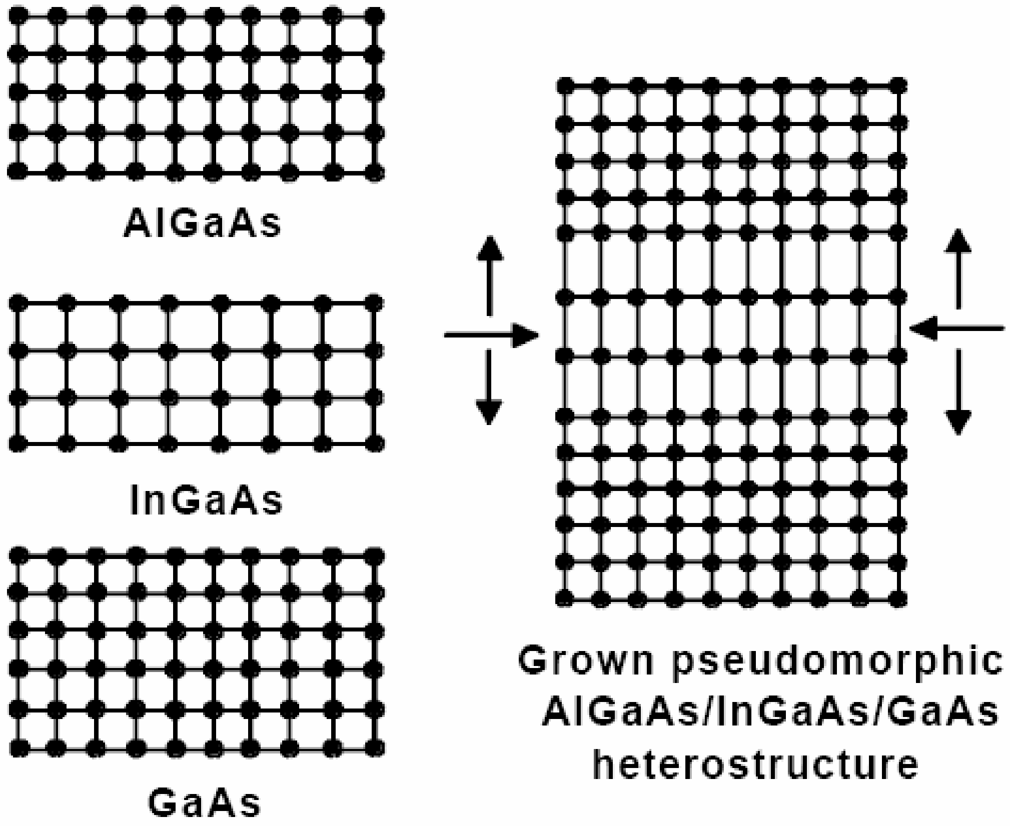
HETEROSTRUCTURES:

Lattice matched
- **AlGaAs/GaAs**
- **$In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/InP$**

Pseudomorphic (strained)
- **$AlGaAs/In_xGa_{1-x}As/GaAs$**
- **$In_{0.52}Al_{0.48}As/In_xGa_{1-x}As/InP$**
- **$Si/Si_{1-x}Ge_x$**
- **$Al_xGa_{1-x}N/GaN$**

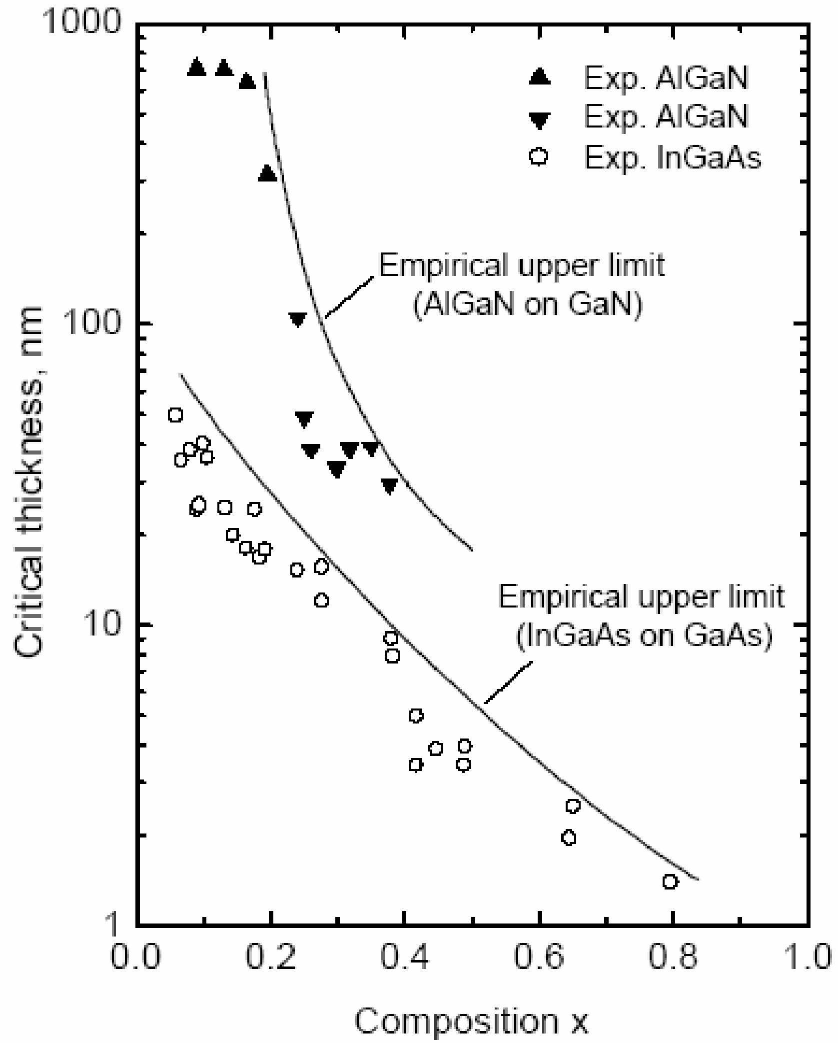
Pseudomorphics Heterostructures

Example: InGaAs/GaAs



The InGaAs layer is STRAINED
(provided the critical thickness is not exceeded)

Critical Thickness



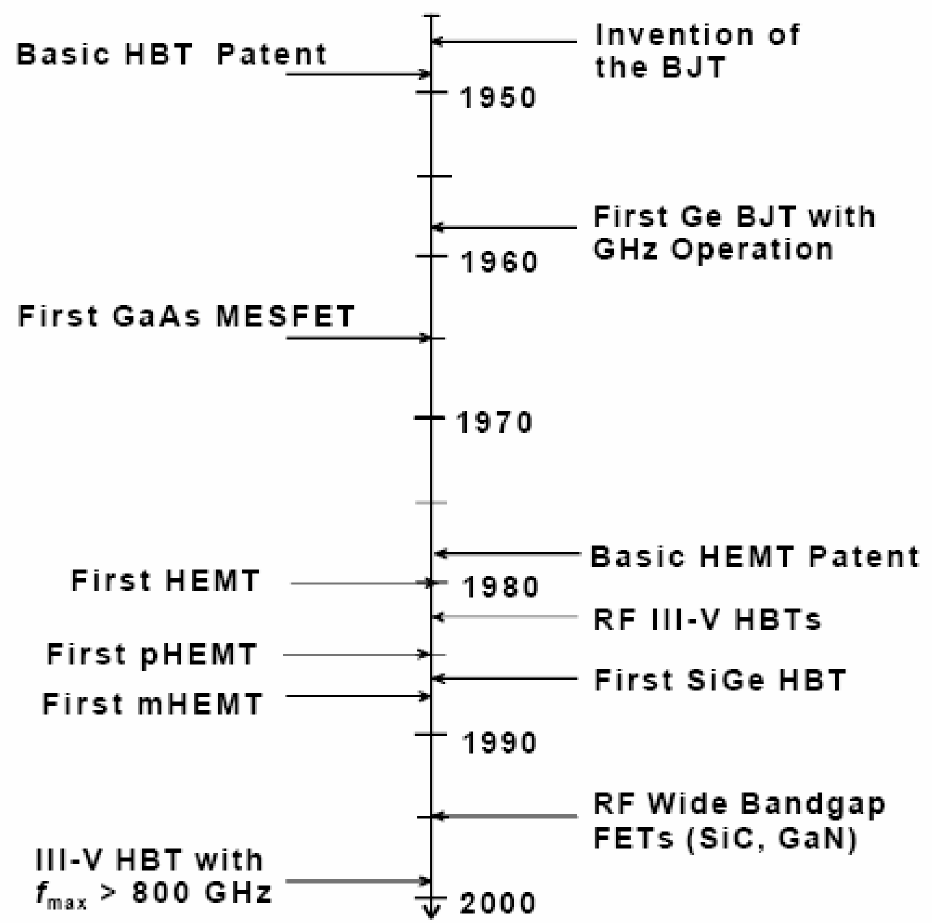
Properties of 2DEGs

Heterojunction Type	μ_0, cm²/Vs	n_S, cm^{-2}	ΔE_G, eV	ΔE_C, eV
$Al_{0.3}Ga_{0.7}As/GaAs$	5400	1.4×10^{12}	0.38	0.22
$Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$	6400	2.2×10^{12}	0.58	0.41
$In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$	10 000	3.0×10^{12}	0.71	0.52
$Al_{0.3}Ga_{0.7}N/GaN$	1 400	1.3×10^{13}	0.6	0.42

Common III-V heterostructures:
- more In in the channel layer leads to higher mobility μ_0
- larger ΔE_C causes a higher higher sheet concentration n_S

Interesting for AlGaN/GaN:
- lower mobility than III-V's
- rather moderate ΔE_C but extremely high n_S - WHY ?
- reason: polarization effects

History and Evolution of RF Transistors



1980 Only two types of RF transistors available:
Si BJTs (f_{op} up to 4 GHz)
GaAs MESFETs (f_{op} 4-18 GHz)

2004 Many different types of RF transistors available:
Bipolar: Si BJTs, SiGe HBTs, III-V HBTs
FET: GaAs MESFETs, III-V HEMTs, Wide Bandgap HEMTs, Si MOSFETs

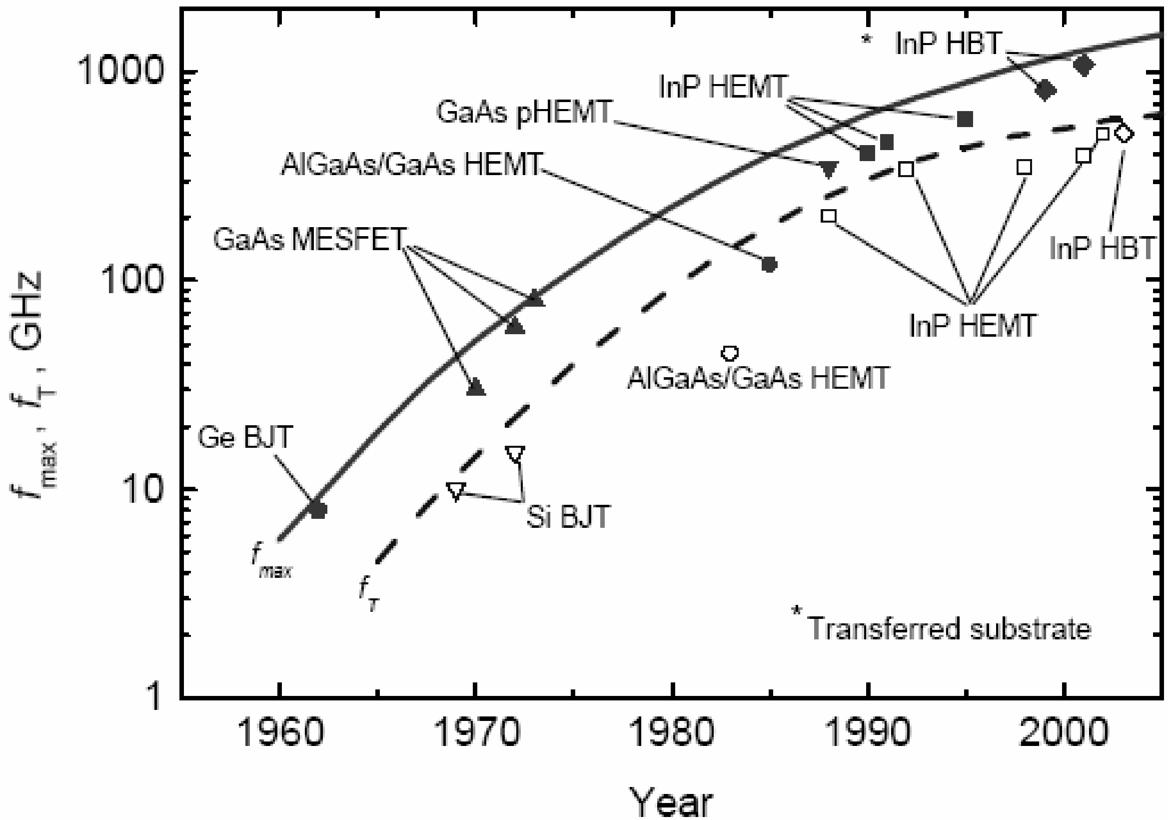
Frequency Limits
III-V FETs: f_{max} > 600 GHz
III-V HBTs: f_{max} 1.1 THz

Trends in the Evolution of RF Transistors

Important Trends:

- Continuous improvement of transistor performance
  - Continuous increase of the frequency limits f_T and f_{max}
  - Increase of the output power at a given frequency
  - Decrease of the minimum noise figure at a given frequency
- During the last 10 years: Shift of the applications of RF systems from defense and space applications to commercial mass markets
  - RF is becoming mainstream
  - Most commercial applications are in the lower GHz range
- Development of low-cost RF transistors for mass consumer markets.
  - Growing role of of Si-based RF transistors
  - For mass markets, cost is an extremely important issue – and Si technology is less expensive that any other semiconductor technology.

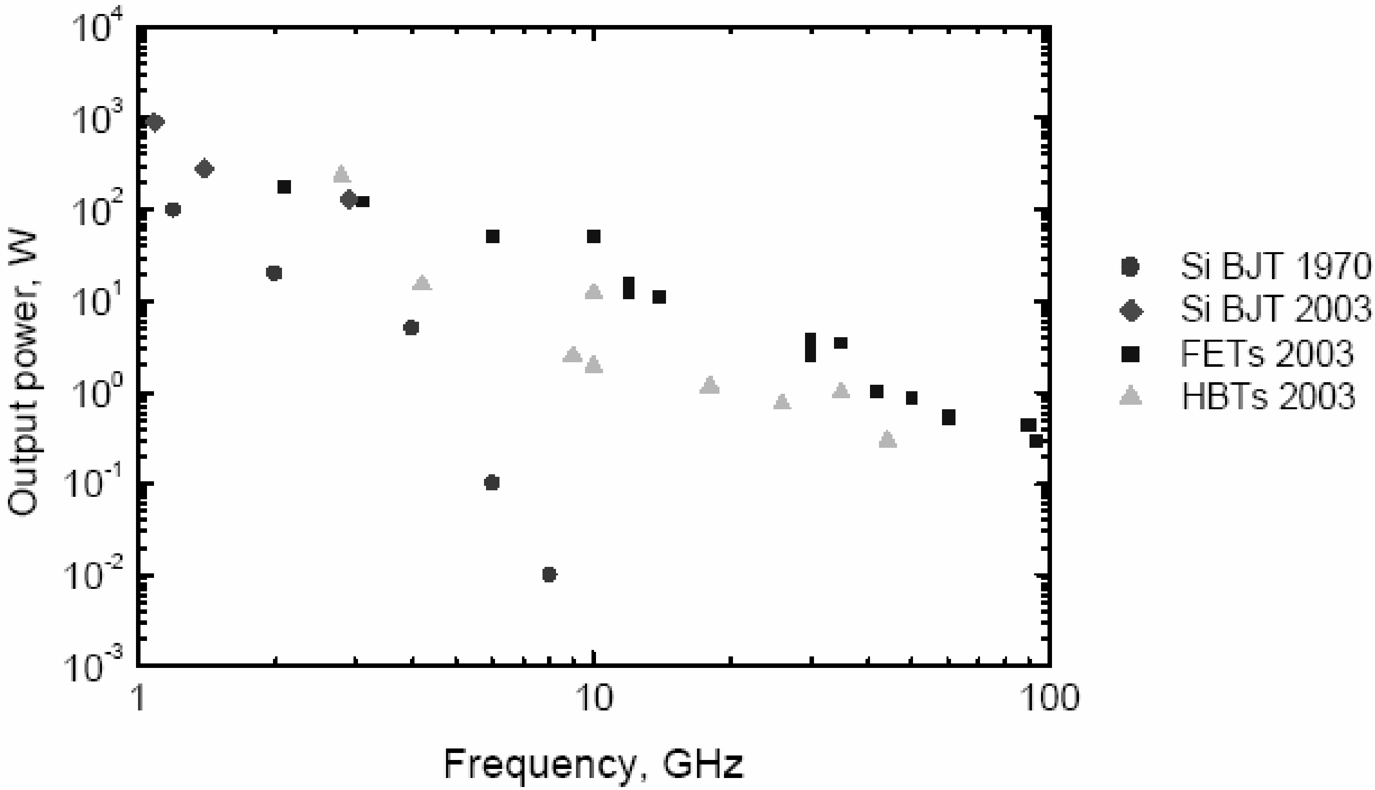
History and Evolution of RF Transistors



Evolution of the frequency limits of RF transistors

Continuous increase of the frequency f_T and f_{max} .

History and Evolution of RF Transistors

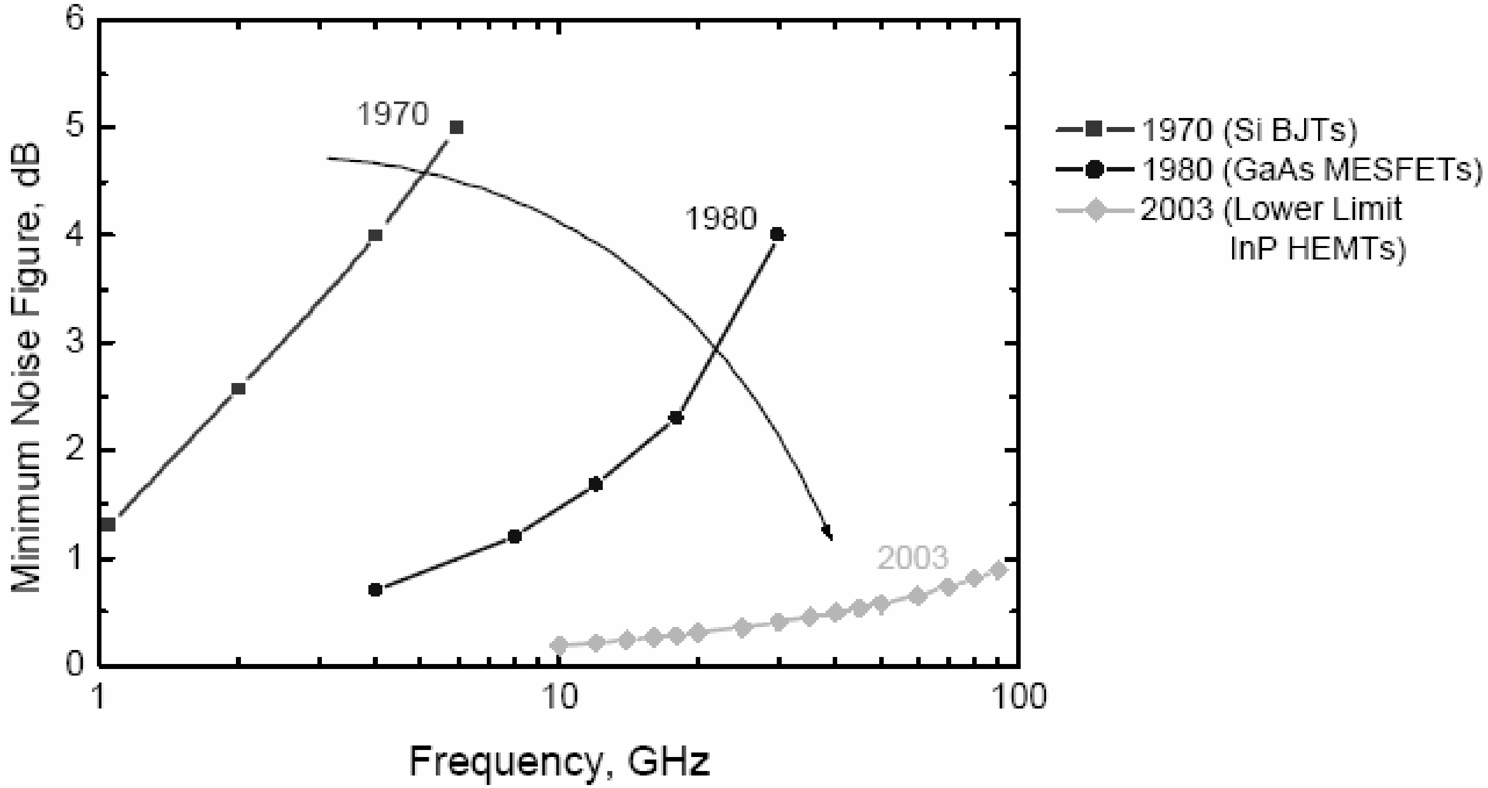


Output power of RF transistors vs frequency

1970: Only Si power BJTs for RF available

2003: Si BJTs, different HBT types, and different FETs types available

History and Evolution of RF Transistors



Minimum noise figure of low-noise RF transistors vs frequency

1970: Only Si power BJTs for RF available

1980: GaAs MESFET least noisy

2003: InP HEMTs least noisy